

Aerial Surveys in the Willapa River Basin
Thermal Infrared and Color Videography

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Report to:

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Final Report

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Introduction

Thermal infrared remote sensing has been demonstrated as a reliable, cost-effective, and accessible technology for monitoring and evaluating stream temperatures from the scale of watersheds to individual habitats (Karalus et. al., 1996; Torgersen et. al. 1999; Torgersen et. al. 2001). In 2001, the Washington Department of Ecology contracted with Watershed Sciences, LLC (WS, LLC) to map and assess stream temperatures in the Willapa River basin in Southwest Washington using thermal infrared (TIR) remote sensing.

This report presents longitudinal temperature profiles for each survey stream as well as a discussion of the thermal features observed in the basin. TIR and associated color video images are included in the report in order to illustrate significant thermal features. An associated ArcView GIS¹ database includes all of the images collected during the survey and is structured to allow analysis at finer scales. Appendix A presents a collection of selected TIR and visible band images from the surveys.

Methods

Data Collection

Data were collected using a TIR sensor and a visible band color video camera co-located in a gyro-stabilized mount that attached to the underside of a helicopter. The helicopter was flown longitudinally along the stream channel with the sensors in a vertical (or near vertical) position. Figure 1 illustrates the extent of the TIR surveys and Table 1 summarizes the dates and times of each survey. The data were collected during the mid-afternoon on August 30, 2001. The surveys were delayed approximately one week due to a rain event that occurred on August 21-22 and increased flows within the basin.

Table 1 - Time, date and distance for the Willapa River Basin Surveys conducted on 30 August 2001.

Stream	Local Time (PM)	miles	Extent
SF Willapa River	2:22 – 2:50	16.6	Mouth to Minnie Cr.
Willapa River	2:54 – 4:28	37.9	Raymond to Willapa Falls
Mill Creek	3:07 – 3:13	2.0	Mouth to Bridge
Trap Creek	3:37 – 3:40	1.1	Mouth to river mile 1
Fork Creek	3:43 – 3:56	5.1	Mouth to Ellis Cr.

¹ Geographic Information System

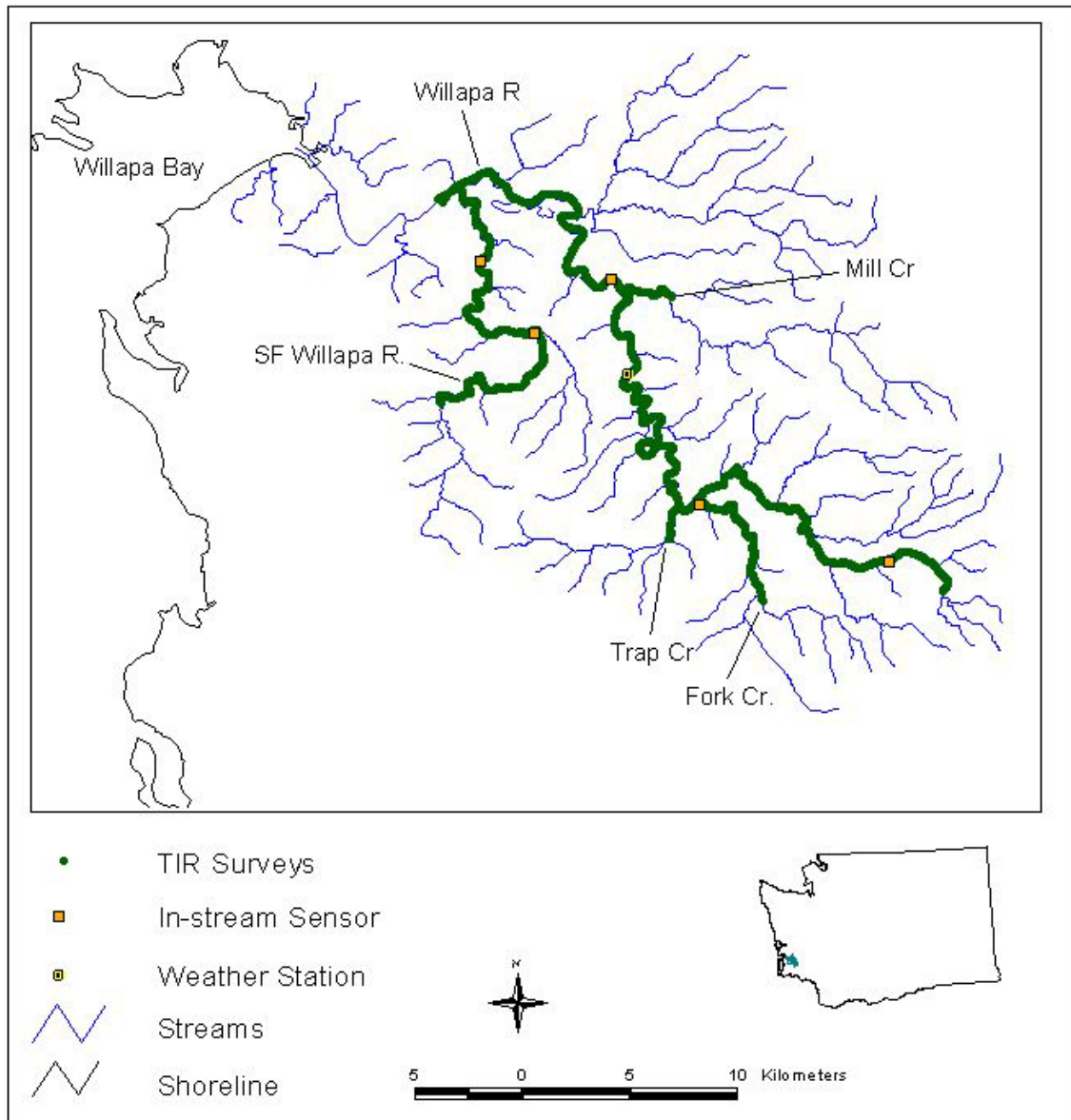


Figure 1 – Map of the Willapa River basin showing streams surveyed using TIR and visible band color video. The map also shows the location of in-stream sensors used to verify the accuracy of the radiant temperatures.

The Willapa River survey started at an altitude of 1800 ft above ground level (AGL) near the tidewater but dropped to 1400 ft AGL as the survey progressed upstream. At 1800 ft, the image has a ground width of approximately 190 meters and a pixel resolution of 0.4 meters. At 1400 ft, the image presents a ground area of 150 meters wide and a pixel size of 0.25 meters. The tributaries including the SF Willapa River were surveyed at a flight altitude of 1200 and 1400 ft AGL.

TIR images were collected digitally and recorded directly from the sensor to an on-board computer. The TIR sensor detects emitted radiation at wavelengths from 8-12 microns and records the level of emitted radiation in the form of an image. Each image pixel contains a measured value that can be directly converted to a temperature. The raw TIR images represent the full 12 bit dynamic range of the instrument and were tagged with time and position data provided by a Global Positioning System (GPS). Visible band color images were recorded to an on-board digital videocassette recorder at a rate of 30 frames/second. GPS time and position were encoded on the recorded video. The color video camera was aligned to present the same ground area as the TIR sensor.

WS, LLC distributed five in-stream temperature data loggers (Onset Stowaways) in the basin prior to the survey in order to ground truth (i.e. verify the accuracy of) the radiant temperatures measured by the TIR sensor. The advertised accuracy of the Onset Stowaway is $\pm 0.2^{\circ}\text{C}$. Figure 1 shows the location of the data loggers used to ground truth the imagery. Meteorological conditions (Table 2) were recorded in the basin using a field station located near river mile 22.0 on the Willapa River. Fog was noted along the coast during the early morning; however, sky conditions during the survey were clear with only high-scattered clouds.

Table 2 – Meteorological conditions recorded near river mile 22.0 on the Willapa River for the time of the TIR surveys on August 30, 2001.

<i>Time</i>	<i>Temp (°F)</i>	<i>Temp (°C)</i>	<i>RH (%)</i>
2:00 PM	71.8	22.1	62.7
2:30 PM	74.5	23.6	59.0
3:00 PM	75.2	24.0	54.4
3:30 PM	74.5	23.6	57.0
4:00 PM	73.2	22.9	51.8
4:30 PM	71.8	22.1	54.4
5:00 PM	71.8	22.1	45.5

Data Processing

A computer program was used to create an ArcView GIS point coverage containing the image name, location, and time it was acquired. The coverage provided the basis for assessing the extent of the survey and for integrating with other spatially explicit data layers in the GIS. From the point coverage, WS, LLC identified the images associated with the ground truth locations and extracted temperature values from these images. The radiant temperatures were then compared to the kinetic temperatures from the in-stream data loggers.

The image points were associated with a river kilometer within the GIS environment. The river kilometers were derived from 1:100K “routed” stream covers from the Environmental Protection Agency (EPA). The route measures provide a spatial context for developing longitudinal temperature profiles of stream temperature.

In the laboratory, a computer algorithm was used to convert the raw thermal images (radiance values) to ARC/INFO GRIDS where each GRID cell contained a temperature value. A GIS program was used to display the GRID associated with an image location selected in the point coverage. The GRID was color-coded to visually enhance temperature differences, enabling the user to extract temperature data (Figure 2).

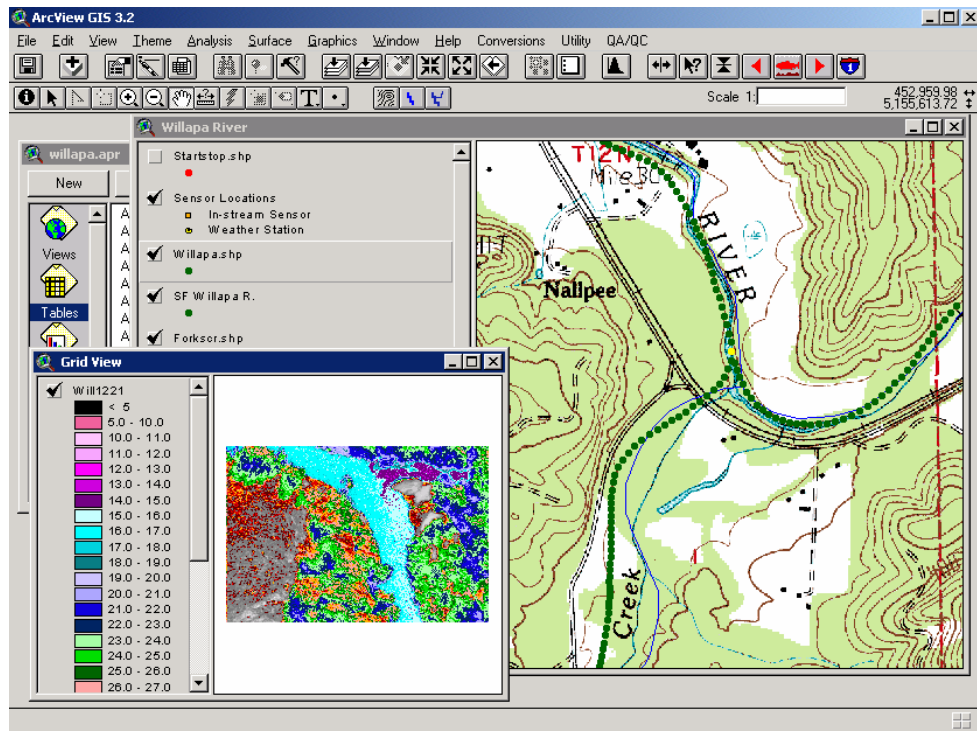


Figure 2 – ArcView 3.2 display showing a color-coded temperature GRID in one window and the geographic location of the GRID in the other. The orientation of the image is always in the flight direction, which in this case is upstream.

Once in the GRID format, the images were analyzed to derive the minimum, maximum, and median stream temperatures. To derive these measures, a computer program was used to sample the GRID cell (temperature) values in the stream channel. Ten sample points were taken longitudinally in the center of the stream channel. Figure 3 provides an example of how temperatures are sampled. The red “x”s on the pseudo-color TIR image show typical sample locations. Samples were taken in a manner that provided complete coverage without sampling the same water twice. Where there were multiple channels, only the main channel (as determined by width and continuity) was sampled. Side channels that had water temperatures different than the main channel were sampled as tributaries. For each sampled image, the sample minimum, maximum, median, and standard deviation were recorded directly to the point coverage attribute file. The median value is the most useful measure of stream temperatures because it minimizes the effect of extreme values.

The temperature of tributaries and other detectable surface inflows were also sampled from images. These inflows were sampled at their mouth using the same techniques described for sampling the main channel. If possible, the surface inflows were identified on the USGS 24K base maps. The inflow name and median temperature were then entered into the point coverage attribute file.

Visible band images corresponding to the TIR images were extracted from the database using a computer-based frame grabber. The images were captured to correspond to the TIR images and provide a complete coverage of the stream. The video images were “linked” to the corresponding thermal image frame in the ArcView GIS environment.

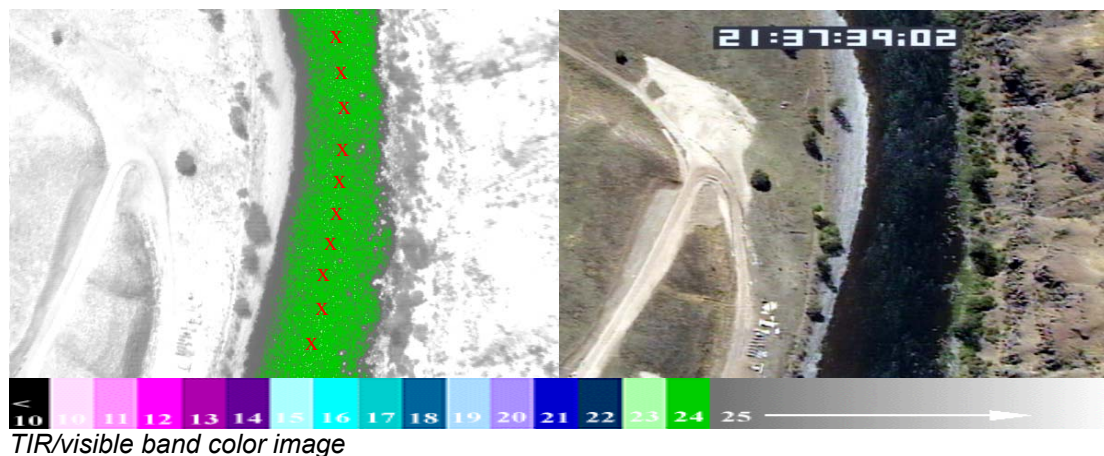


Figure 3 – Example of a TIR and visible band image pair showing typical temperature sampling locations. Temperatures are presented in °C.

Data Limitations

TIR sensors measure thermal infrared energy emitted at the water's surface. Since water is essentially opaque to thermal infrared wavelengths, the sensor is only measuring water surface temperature. TIR data accurately represents bulk water temperatures in reaches where the water column is thoroughly mixed, however, thermal stratification can form in reaches that have little or no mixing. In the Willapa Basin, possible thermal stratification was noted in the lower 3.8 miles of the South Fork Willapa River. In general, however, thermal stratification was not considered an issue in evaluating spatial temperature patterns in the Willapa River and its tributaries.

The TIR sensor cannot see through vegetative canopy. Vegetation occasionally masked the stream during near the headwater reaches of the Willapa River and S.F. Willapa River surveys. Even in heavily canopied areas, the streams were intermittently visible through breaks in the canopy allowing the development of a continuous longitudinal profile. The major issue of vegetation masking in these areas was identifying small tributaries and other thermal features in the riparian zone.

Results

Thermal Accuracy

Temperatures from the in-stream data loggers were compared to radiant temperatures derived from the imagery for each survey (Table 3). The data were assessed at the time the image was acquired, with the radiant values representing the median of 10 points sampled from the image at the data logger location. If a consistent difference was observed for all in-stream sensors, the parameters used to convert radiant values to temperatures were adjusted to provide a better fit to the in-stream sensors.

Table 3 – Comparison of ground-truth water temperatures with radiant temperatures derived from the TIR images, 30 August 2001. Temperatures are reported in °C and river miles (rm) are cited for locations.

Location	Image Frame	Time	In-stream Temp. Ts	Radiant Temp Tr	Difference Ts – Tr
SF Willapa R @ rm 4.4	sfw0378	2:27 PM	15.3	15.0	0.3
SF Willapa R @ rm 10.3	sfw0705	2:38 PM	14.0	14.4	-0.4
Willapa R. @ rm 18.0	will0372	3:06 PM	19.3	18.1	1.2
Fork Cr. @ mouth	will1359	3:42 PM	15.1	15.7	-0.6
Willapa @ rm 41.9	will2352	4:22 PM	15.4	16.1	-0.7

The two in-stream data loggers located in the SF Willapa River were consistent with the radiant temperatures measured from the thermal imagery ($\pm 0.4^{\circ}\text{C}$). The calibration parameters used to convert the imagery for the SF Willapa River were adjusted slightly to provide a best fit to the in-stream sensors located in the Willapa River. Larger differences (-0.7°C to 1.2°C) were noted between radiant temperatures and in-stream temperatures in the Willapa River. While the difference was larger than the average accuracy observed during river surveys in the Pacific Northwest over the past four years (Torgersen et. al. 2001), the accuracies are typical of aerial surveys conducted on other coastal rivers where meteorological gradients exist between the coastal and inland areas. The impact that the temperature differences had on the observed temperature patterns is discussed later in this report.

Longitudinal Temperature Profiles

Willapa River

The median temperatures for each sampled image of the Willapa River were plotted versus the corresponding river mile (Figure 4). The plot also contains the median temperature of all surface water inflows that were visible in the imagery where they input to the Willapa River. Tributaries are labeled in Figure 4 by stream mile with their name and temperature listed in Table 4. The profile shows the spatial distribution of stream temperatures along the survey route.

The Willapa River was cool (13.9°C) near the end of the survey (river mile 44.0) and warmed rapidly in the downstream direction reaching a local maximum of 17.9°C at river mile 40.8. Vegetation masked the stream at several locations within this reach and made it difficult to view the confluence of several tributaries including Patten Creek. An unnamed tributary at river mile 40.8 was a cooling source to the Willapa River and Falls Creek at river mile 39.7 further lowered mainstream temperatures to approximately 16.1°C . Stream temperatures increase between river miles 39.2 and 37.1, but then cool again between river mile 37.1 and 35.4. The source of this cooling trend was not apparent from the imagery. Half Moon Creek was located within this reach and was not visible enough to sample. However, there was no plume or detectable drop in the longitudinal profile that would indicate that Half Moon Creek contributes significantly to this trend.

Fork Creek and Trap Creek enter the Willapa River at miles 32.0 and 31.4 respectively and contribute to a cooling trend observed between river miles 33.0 and 31.0. The observed cooling trend starts prior to the confluence of Fork Creek indicating that factors other than surface water inputs are influencing mainstream temperatures within this reach. Stream temperatures increase downstream of Trap Creek and reach $\approx 17.0^{\circ}\text{C}$ at river mile 26.6. Over the next six miles, bulk stream temperatures remain

relatively consistent (17.1°C on average) varying less than $\pm 0.5^{\circ}\text{C}$. Stream temperatures rise between river mile 20.8 and 18.8, but then cool by $\approx 2.2^{\circ}\text{C}$ between river miles 18.8 and 15.0. Mill Creek contributes cooler water to Willapa River at mile 18.6, but there were no other tributaries detected through this reach. The profile shows an apparent temperature increase ($\approx 1.5^{\circ}\text{C}$) followed by a decrease in stream temperatures between river miles 15.0 and 13.5. From river mile 13.5, stream temperatures warm steadily to the start of the survey.

A total of 13 tributaries and 3 side channel features were sampled. Of the 13 tributaries, nine contributed water that was cooler than the mainstream. All of the sampled tributaries and side channels that contributed warmer water were located downstream of river miles 12.2. The six tributaries sampled upstream of river mile 12.2 were sources of thermal cooling and significant in defining spatial temperature patterns at the watershed scale.

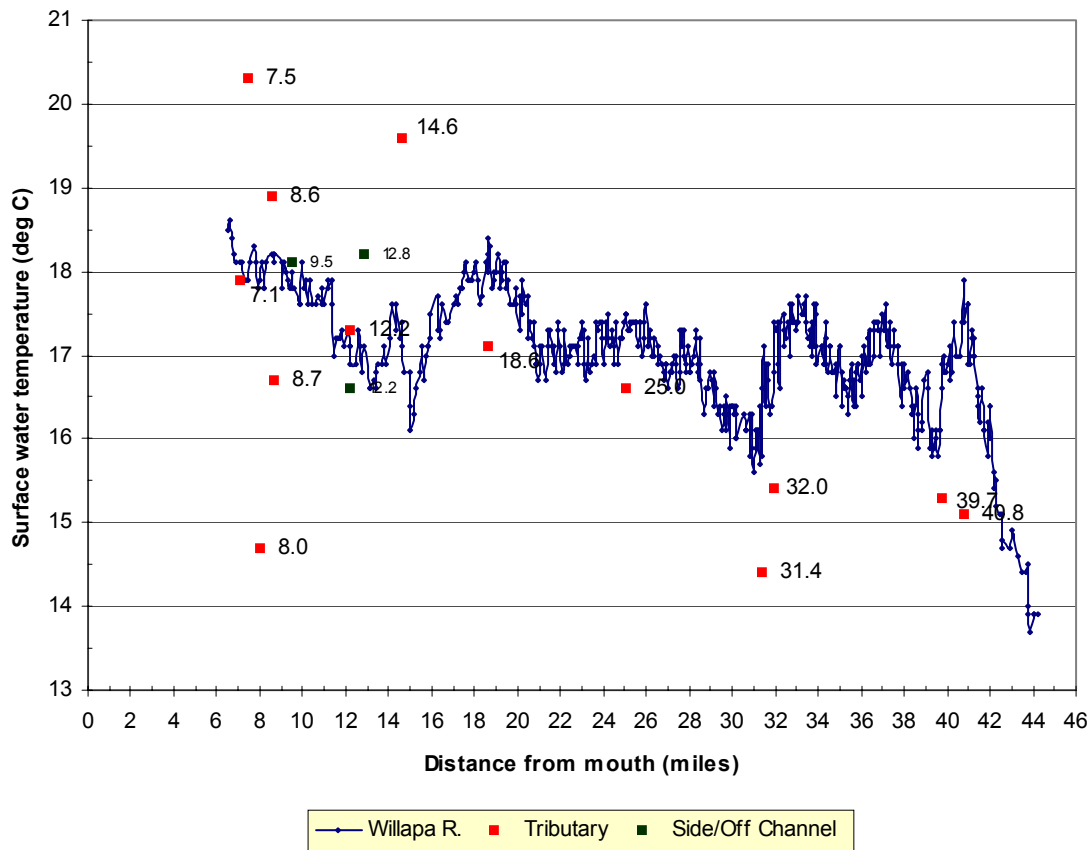


Figure 4 - Median channel temperatures versus river mile for the Willapa River along with tributary locations and temperatures (8/30/01). Tributary locations are labeled by river mile.

Table 4 - Tributary temperatures for the Willapa River, WA. Miles correspond to data labels shown in Figure 4.

Tributary Name	Image	km	mile	Tributary Temp °C	Willapa R. Temp °C	Difference °C
No Name (RB)	will0019	11.4	7.1	17.9	18.1	-0.2
No Name (RB)	will0032	12.0	7.5	20.3	17.9	2.4
No Name (RB)	will0048	12.8	8.0	14.7	17.9	-3.2
Elk Creek (RB)	will0064	13.8	8.6	18.9	18.2	0.7
No Name (LB)	will0070	13.9	8.7	16.7	18.2	-1.5
Wilson Creek (RB)	will0189	19.6	12.2	17.3	17.1	0.2
No Name (LB)	will0268	23.6	14.6	19.6	17.1	2.5
Mill Creek (RB)	will0395	29.9	18.6	17.1	18.2	-1.1
Stringer Creek (LB)	will0887	40.3	25.0	16.6	17.5	-0.9
Trap Creek (LB)	will1222	50.6	31.4	14.4	16.6	-2.2
Fork Creek (LB)	will1350	51.5	32.0	15.4	17.4	-2.0
Falls Creek (LB)	will2232	63.9	39.7	15.3	16.6	-1.3
No Name (LB)	will2286	65.6	40.8	15.1	17.9	-2.8
Side/off Channel						
Ellis Slough (LB)	will0099	15.3	9.5	18.1	17.8	0.3
Side Channel (RB)	will0193	19.7	12.2	16.6	16.9	-0.3
Inlet (LB)	will0210	20.6	12.8	18.2	17.1	1.1

South Fork Willapa River

A longitudinal temperature profile was developed for the 16.6 miles of the South Fork (SF) Willapa River (Figure 5). Stream temperatures were relatively consistent ($\approx 13.8^{\circ}\text{C}$) between river miles 16.6 and 11.6. Mainstream temperatures increased by approximately 1.0°C between river miles 11.6 and 9.7 and then remained relatively consistent to the confluence of Fall Creek. Fall Creek was a source of thermal cooling to the South Fork Willapa River and lowered mainstream temperatures slightly ($\approx 0.7^{\circ}\text{C}$). Stream temperatures increased by approximately 1.0°C between river mile 8.6 and 3.8.

At river mile 3.8, stream temperatures showed a rapid increase (3.5°C) over the next mile. The location of the temperature gain corresponds to the start of a lower gradient marsh area that extends from river mile 4.0 to the mouth. Analysis of the imagery showed thermal mixing near river mile 3.7, which may indicate a cooler sub-layer (*reference Appendix A*). Similar areas of mixing were noted at different locations throughout this reach. While deep, slow moving channels have the potential for thermal stratification, the images did not show random surface temperature patterns normally associated with thermally stratified areas in moving water. Tidal influence might also be

a factor in the observed temperature increase through this reach. However, tide levels and upstream influences were not investigated as part of this analysis.

Fall Creek was the only tributary sampled (excluding the Willapa River) during the analysis of the SF Willapa River. Other mapped tributaries were not sampled because their size and/or canopy masking precluded an accurate temperature sample. Ultimately, there was no significant temperature difference between SF Willapa Creek and the main stem Willapa River at the confluence.

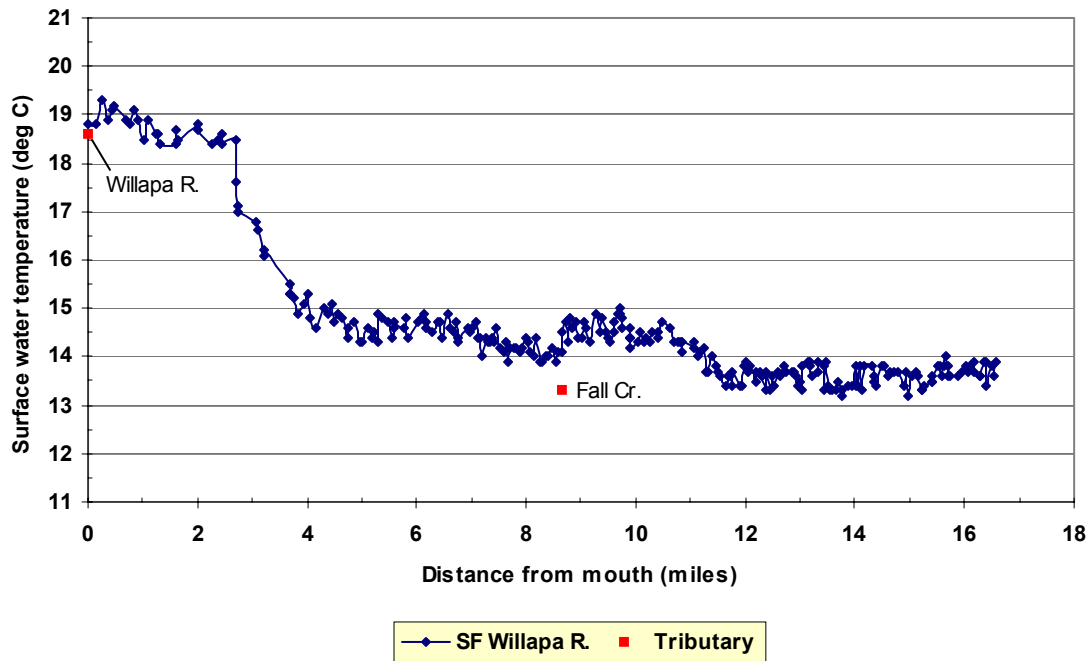


Figure 5 - Median channel temperatures versus river mile for the South Fork Willapa River along with tributary locations and temperatures (8/30/01).

Tributaries

Longitudinal temperature profiles were developed for the surveyed segments of Mill Creek, Trap Creek, and Fork Creek (Figures 6, 7, and 8 respectively). The profiles show how stream temperatures varied over the survey reach as well as the temperature of the Willapa River at the confluence.

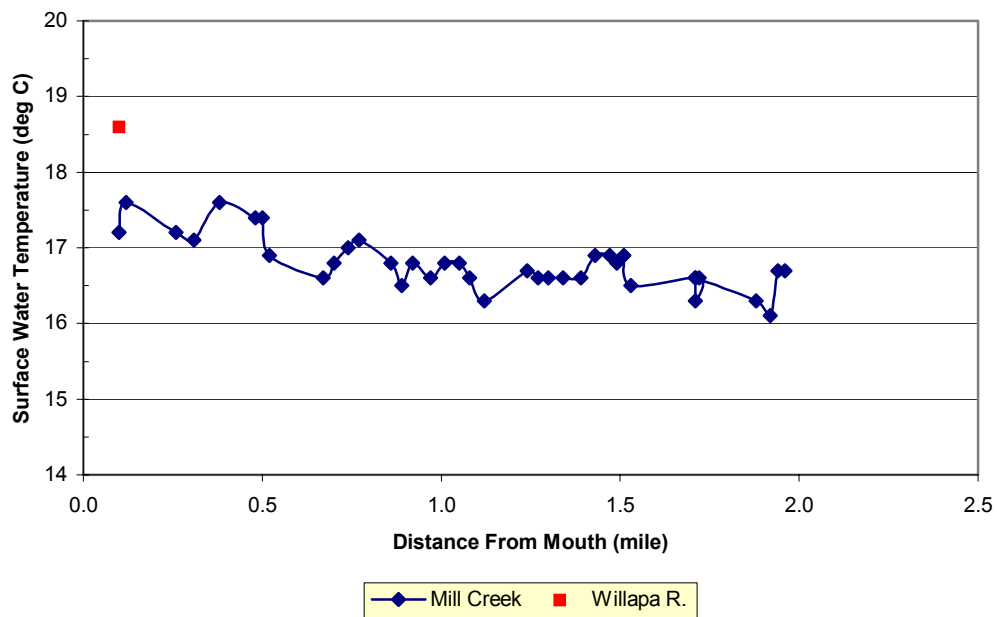


Figure 6 - Median channel temperatures versus river mile for Mill Creek, WA (8/30/01).

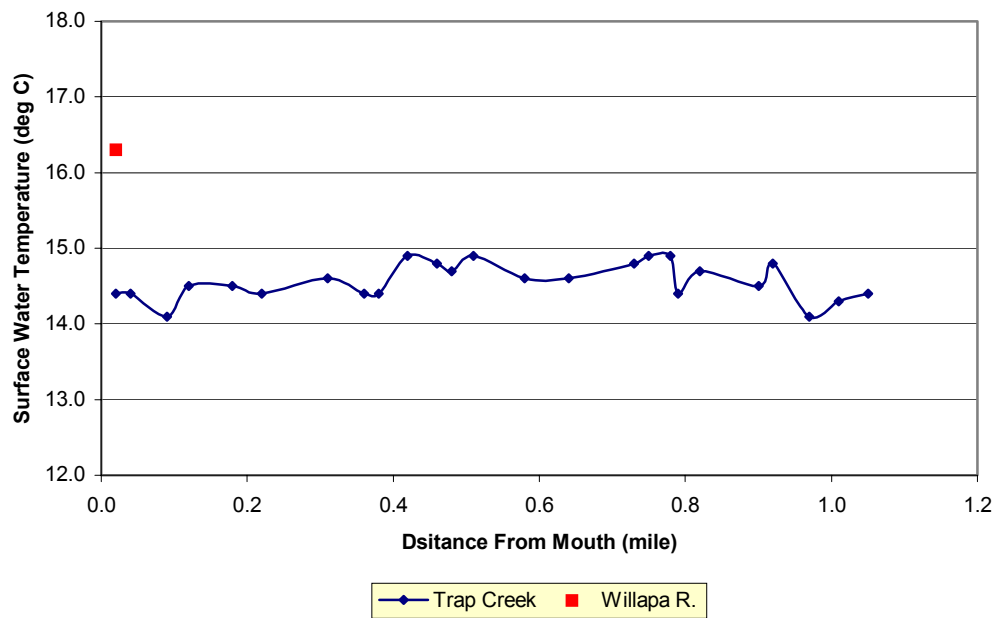


Figure 7 - Median channel temperatures versus river mile for Trap Creek, WA (8/30/01).

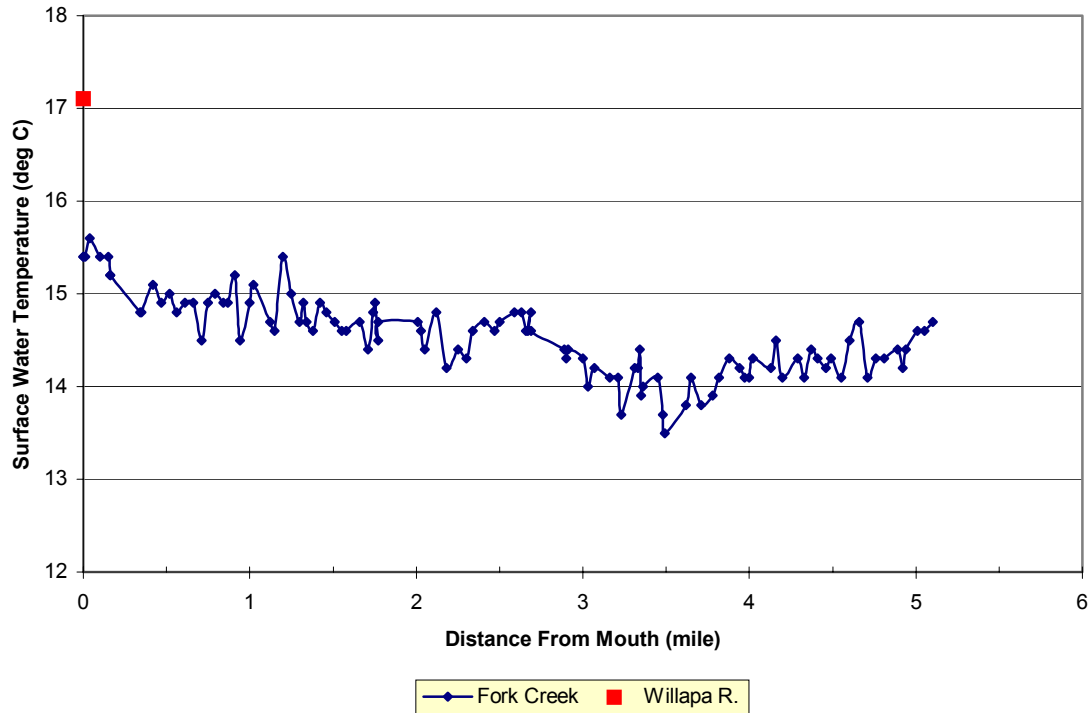


Figure 8 - Median channel temperatures versus river mile for Fork Creek, WA (8/30/01).

Discussion

TIR remote sensing surveys were used to map stream temperatures for the Willapa River and selected tributaries in the basin. The data were collected on August 30th during the mid-afternoon in order to capture heat of the day, heat of the summer conditions. A rain event on August 20-21 delayed the surveys, increased flows, and presumably altered the stream's thermal regime when compared to earlier in the month. However, TIR surveys in other basins have shown that while absolute temperatures change, patterns of warming and cooling remain fixed spatially. The temperature patterns presented in this report (and in the associated database) should be further evaluated within the context of seasonal in-stream data loggers. How do temperatures observed in the temperature profiles compare to seasonal maximums? How do the absolute temperatures in the cool reaches change and do these areas represent thermal refuge for cold-water fish species during the summer months?

The Willapa River showed thermal spatial variability along the longitudinal temperature profile. Several cold-water tributaries contribute to the observed temperature patterns. However, surface inputs did not fully account for spatial variability in the stream temperature profile. The SF Willapa River showed a net temperature gain of 1.5°C

for the first 12 miles (starting at the upstream end of the survey) with only local variability. On both the SF and main stem Willapa River, canopy was a factor in the ability to detect and interpret thermal features within the riparian zone for the upper reaches. In addition, the tidal influence should be considered during follow-on analysis of stream temperature patterns in the lower reaches of both streams.

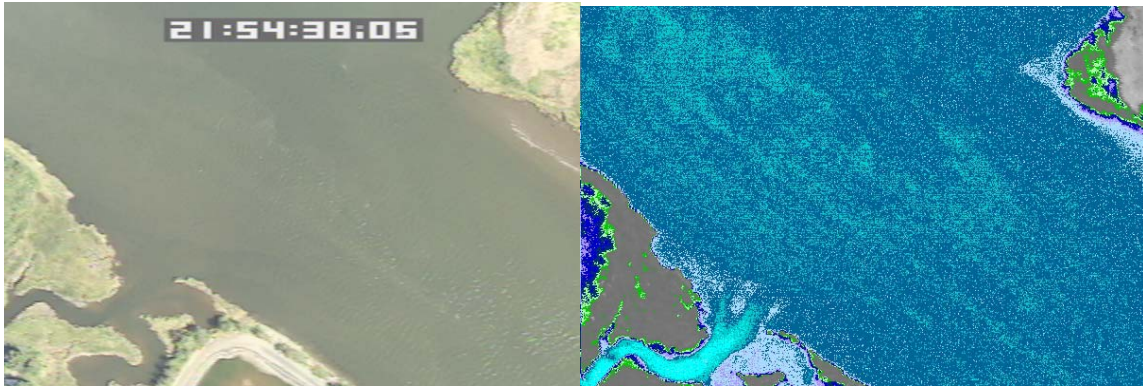
The TIR surveys lay the basic groundwork to integrate the total daily maximum load (TMDL) process into watershed planning and restoration. In particular, water temperature modeling can provide a powerful tool to address the biophysical parameters that are driving stream temperature patterns and suggest multiple pathways for remediation. In addition, the longitudinal temperature patterns provide a robust and rigorous template to construct a monitoring program from, in particular the deployment of in-stream temperature sensors.

Bibliography

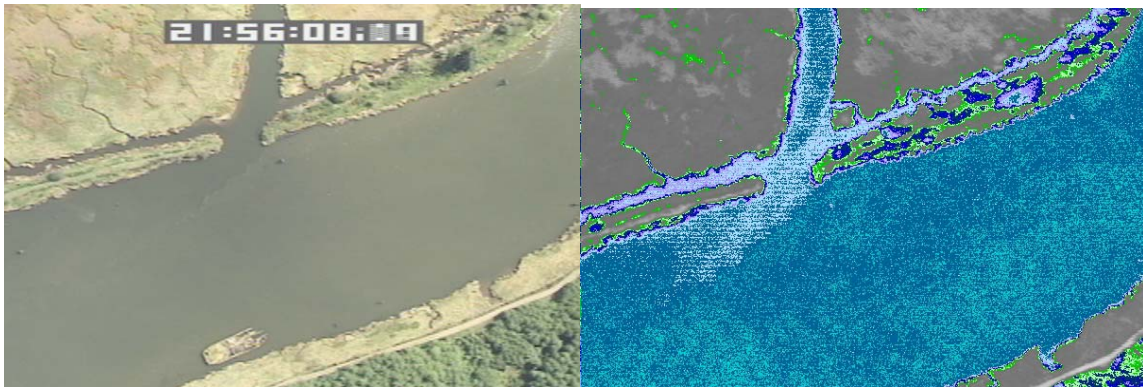
- Karalus, R.S., M.A. Flood, B.A. McIntosh, and N.J. Poage. 1996. ETI surface water quality monitoring technologies demonstration. Final Report. Las Vegas, NV: Environmental Protection Agency.
- Torgersen, C.E., D.M. Price, H.W. Li, and B.A. McIntosh. 1999. Multiscale thermal refugia and stream habitat associates of Chinook salmon in Northeastern Oregon. *Ecological Applications*. 9(1), pp 301 – 319.
- Torgersen, C.E., R. Faux, B.A. McIntosh, N. Poage, and D.J. Norton. 2001. Airborne thermal remote sensing for water temperature assessment in rivers and streams. *Remote Sensing of Environment* 76(3): 386-398.

Appendix A - Selected Images

Willapa River

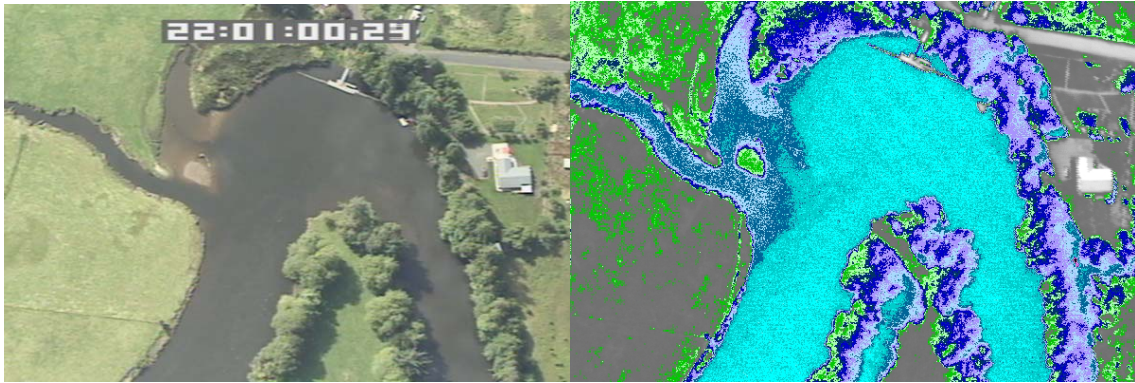


Frame: will0019 – Visible band/TIR image pair showing a surface inflow to the right bank of the Willapa River (18.1°C) at river mile 7.1. The inflow appears too consistent of two separate sources, which converge prior to entering the Willapa River. The upstream source measures 17.9°C while the one downstream measures 19.8°C .

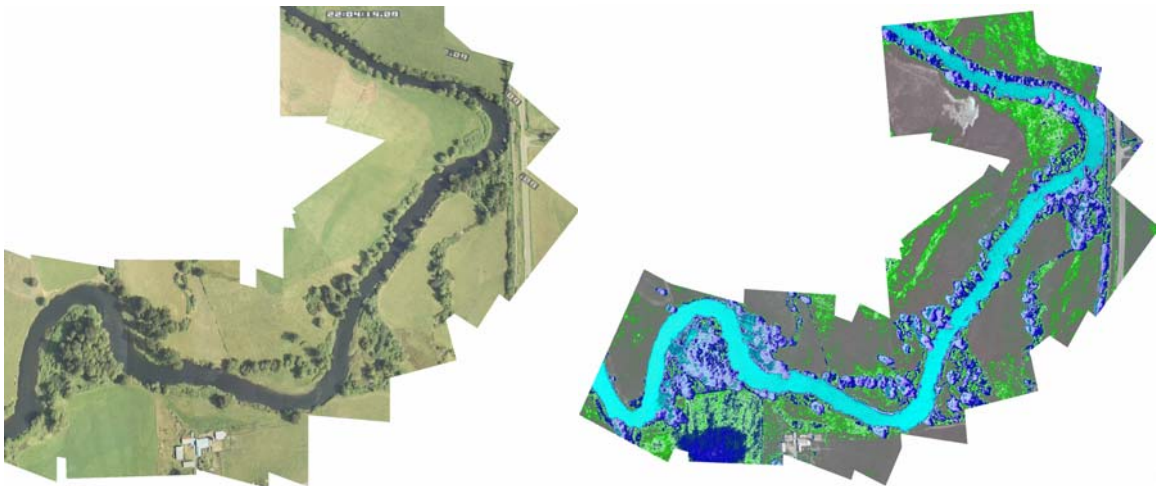


Frame: will0064 – Visible band/TIR image pair showing the confluence of Elk Creek (18.9°C) and the Willapa River (18.2°C) at river mile 9. The Willapa River flows from right to left in the image.

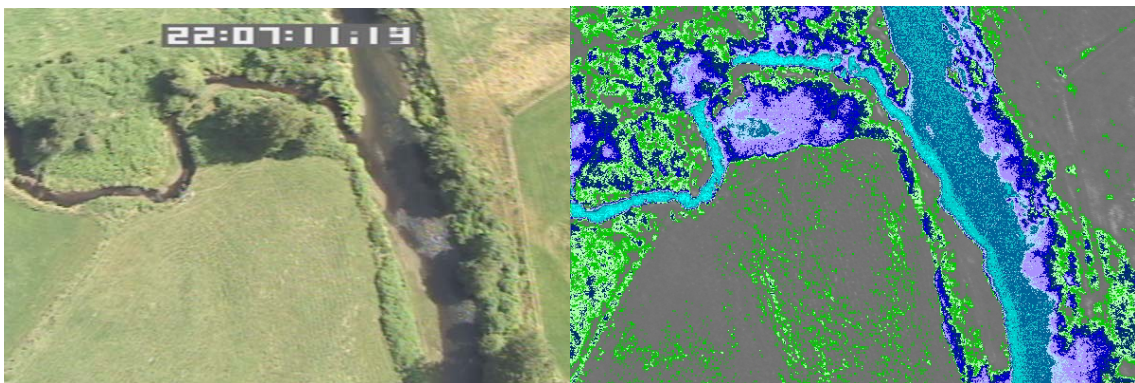




Frame: will0210 – Visible band/TIR image showing a warmer inlet (18.2°) on the right bank of the Willapa (17.1°C) at river mile 12.8.

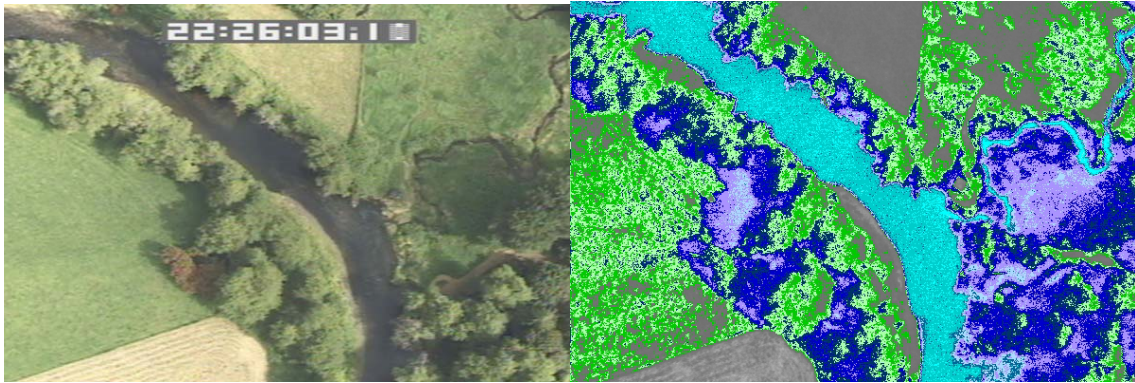


Frame: will0279-0307 – Image mosaic showing the Willapa River between river miles 15.9 to 15.0. An apparent temperature decrease (17.5 to 16.3°C) was observed through this reach. The source of the apparent cooling was unknown.

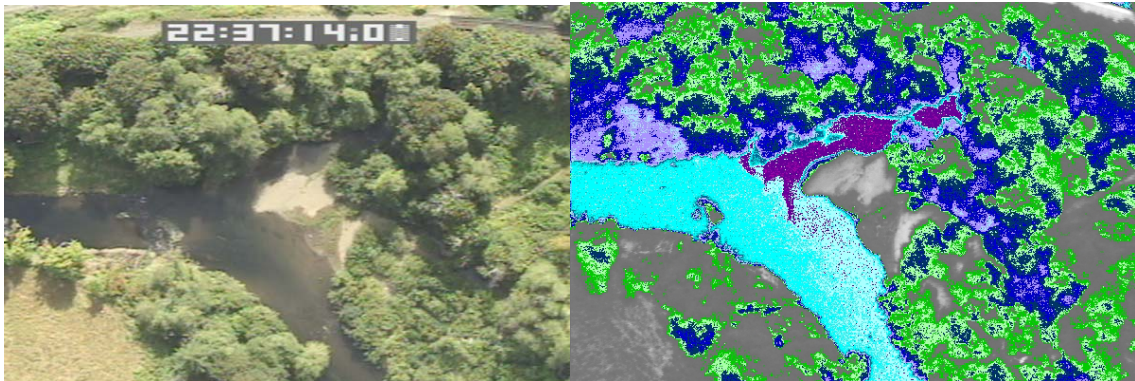


Frame: will0395 – Visible band/TIR image pair shows the confluence of Mill Creek (17.1°C) and the Willapa River (18.2°C) at river mile 18.6. Flow direction is from top to bottom of the image.

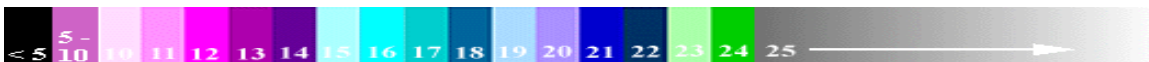


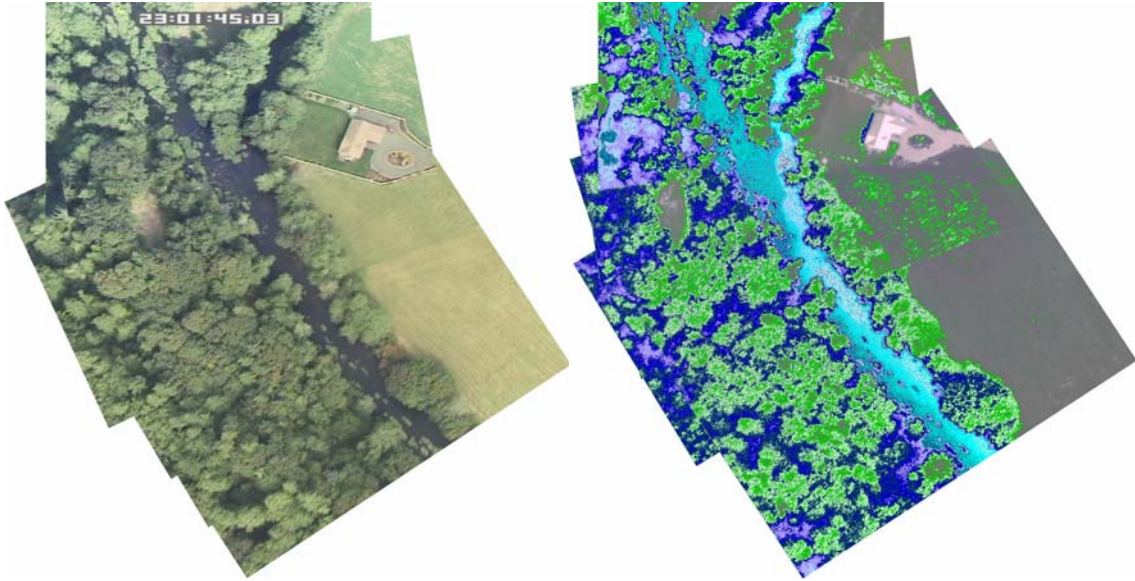


Frame: will0887 – Visible band/TIR image pair showing the confluence of Stringer Creek (16.6°C) and the Willapa River (17.5°C) at river mile 25. The Willapa River flows from the top to bottom of the image and Stringer Creek enter along the left bank.

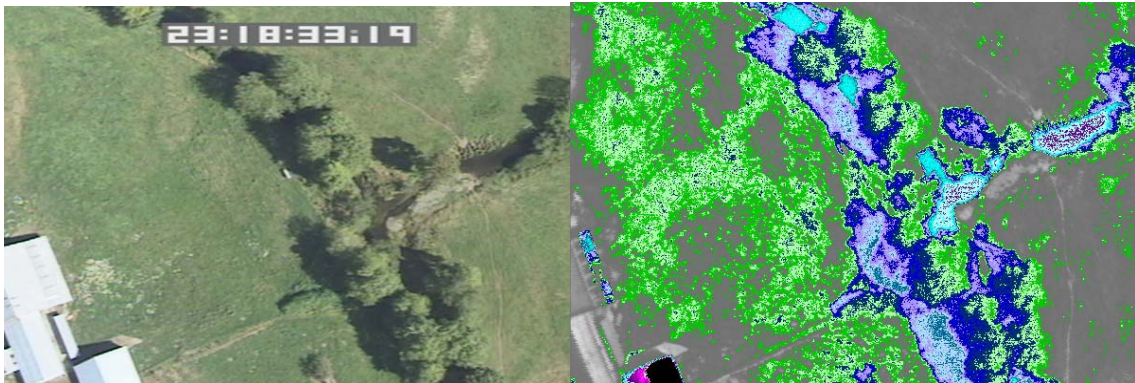


Frame: will1222 –Trap Creek (14.4°C) enters the left bank of the Willapa River (16.6°C) at river mile 31.4. Trap Creek flows in from the right side of the image and the Willapa River flows from the top to the bottom of the image.

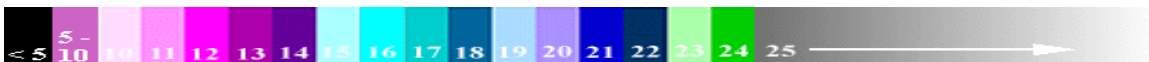




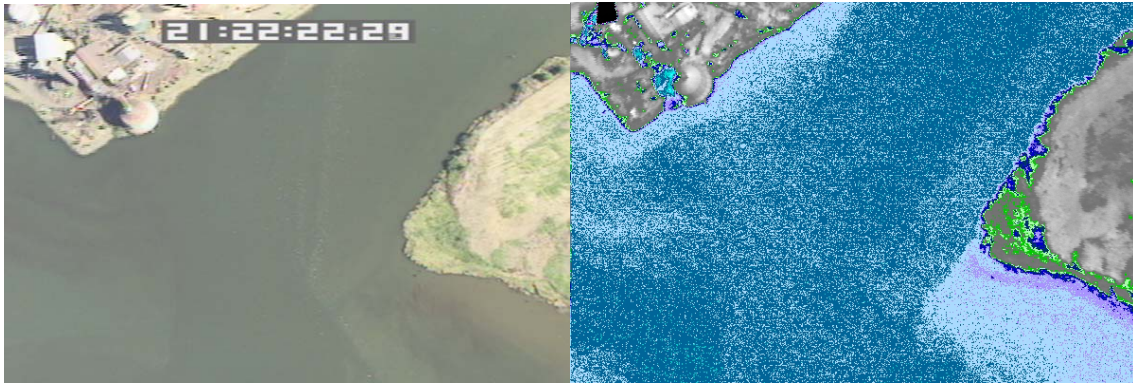
Frame: will1347-1351&1728 – These images show the confluence of Fork Creek (15.4°C) and the Willapa River (17.4°C) at river mile 32. The Willapa River flows from the top to the bottom of the image.



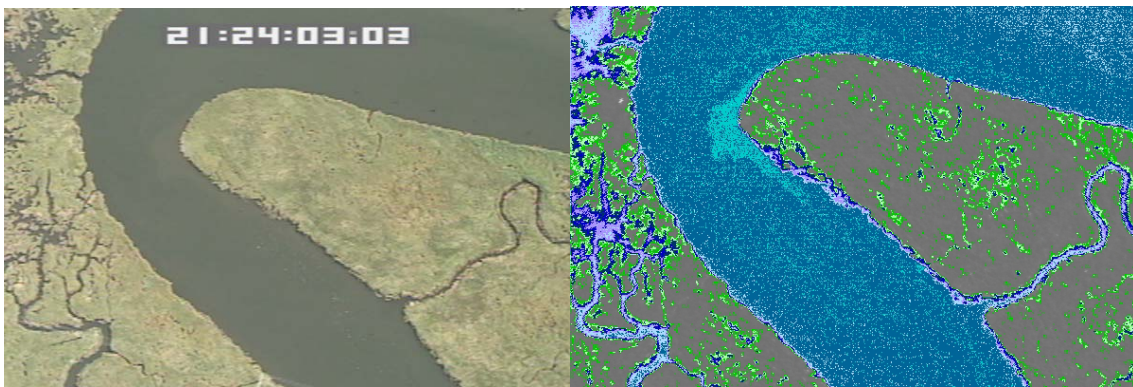
Frame: will2232 – Visible band/TIR image showing the confluence of Falls Creek (15.3°C) and the Willapa River (16.6°C) at river mile 39.7. The Willapa River flows from the top to bottom of the image and Falls Creek enter along the left bank.



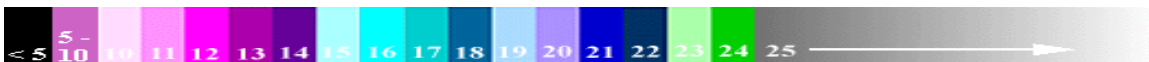
South Fork (SF) Willapa River

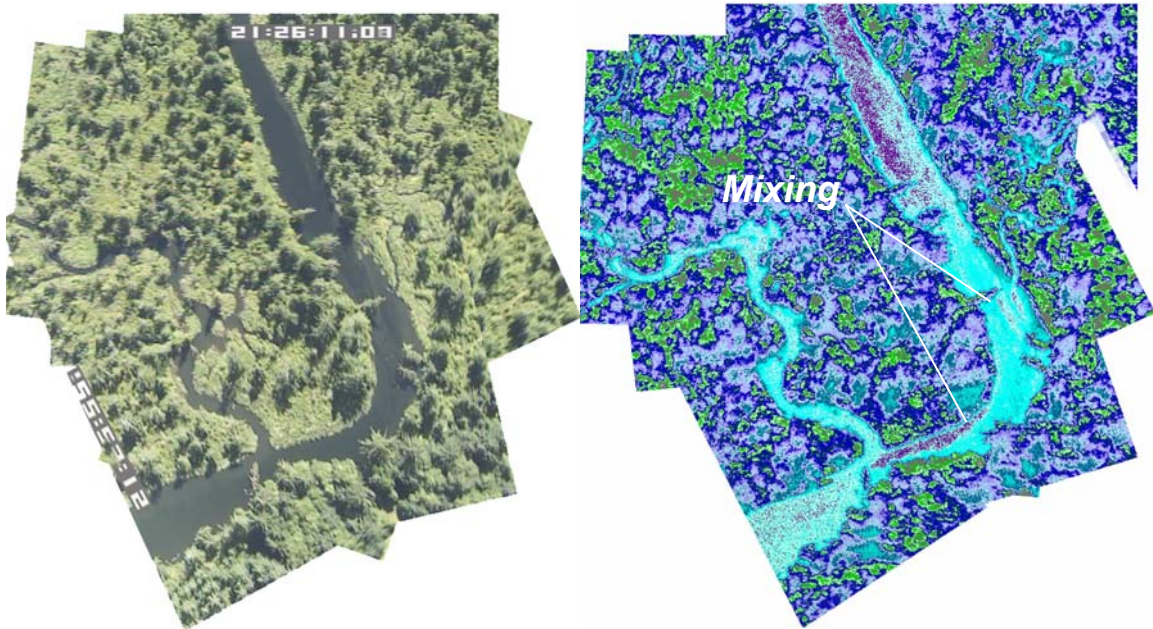


Frame: sfw0235 – Visible band/TIR image pair showing the confluence of the SF Willapa River (18.8°C) and the Willapa River (18.6°C). The SF flows in from the right side of the image.

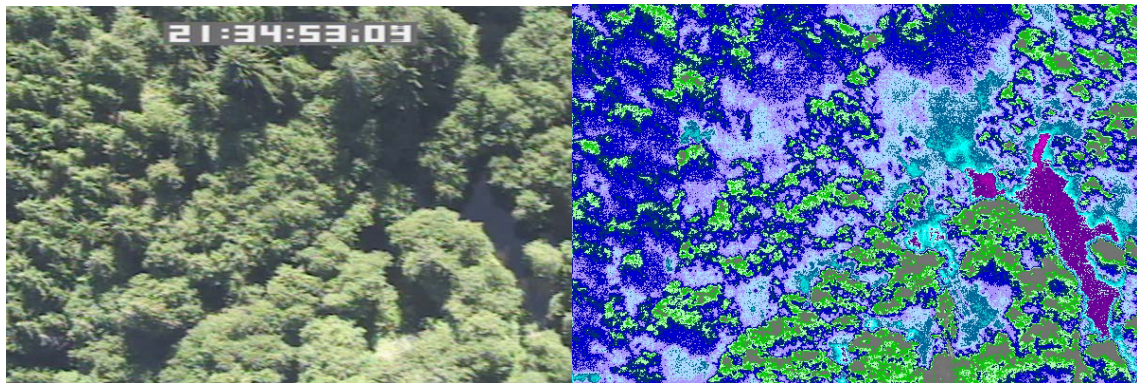


Frame: sfw0285 – In these images, a cold region is visible on the left bank and numerous small inlets are visible on both banks of the SF Willapa River (18.4°C) at river mile 1.6. The cold region indicates possible mixing on the bend and possible thermal stratification within this reach.





Frame: sfw0341-0349 – Image mosaic showing temperature increase near river mile 3.8 on the SF Willapa River. The rapid increase and the areas of mixing through this segment indicate possible thermal stratification.



Frame: sfw0610 – Visible/TIR image pair showing the confluence of Fall Creek (13.3°C) and the SF Willapa River (14.5°C) at river mile 8.6. Fall Creek enters the SF Willapa River along the left bank.

